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Characterization of a Low NO_x Flameless Combustion Burner Using Natural Gas

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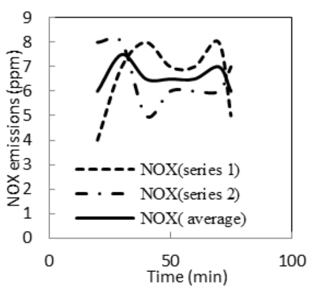
Graphical abstract



Abstract

Flameless combustion is a method that has a great potential in reducing pollutant emission from combustion process. In this work, the operation and emission of a laboratory scale furnace under the flameless combustion regime using natural gas as a fuel was examined. In the experimental setup, the combustor was equipped with parallel jet burner systems with controlled gas fuel and oxidizer. Several ports have been integrated in the combustor to allow for temperature and combustion emission measurement. In the study, a comparison between flameless combustion with and without preheated combustion air has been made. The atmospheric air was heated to near the auto ignition temperature by a coil placed within the furnace assembly. The results show that flameless combustion mode could be obtained with and without preheated combustion air. The results also revealed that the laboratory scale furnace could successfully operate in flameless combustion regime using natural gas as fuel. In terms of emission, it was found that flameless combustion was more effective than the conventional combustion in reducing the rate of NO_X emission.

Keywords: Flameless combustion; low NO_X emission; burner

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1.0 INTRODUCTION

Energy is a basic need of humankind. Modern production of energy is used for applications such as electricity generation, transportation and heat production for heavy industry in the industrialized countries. One of the oldest conversion methods to transform fuel into energy is the combustion. The disadvantage of using fossil fuel in the combustion process is the emission of unwanted pollutants that will consequently create adverse effects on environment and human health[1,2]. Today, reducing the pollutant emissions from the combustion process and saving energy are two common challenges in energy conversion process and in the design of modern combustion systems.

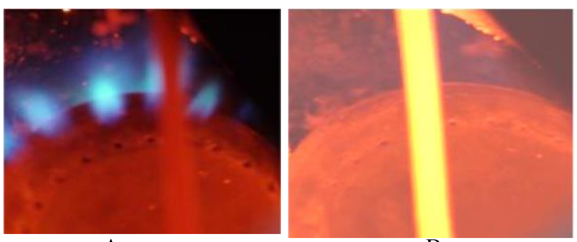
For the last two decades, the combustion technology acquires constant improvements, and as a result a new combustion technology known as 'Flameless Combustion' was developed; it was dividing into two categories. The first category is the combustion process which known today as High Temperature Air Combustion (HiTAC), Moderate or Intense Low Oxygen Dilution (MILD) Combustion, Flameless Oxidation (FLOX)[3], Colorless Combustion or Normal Temperature Air Flameless Combustion (NTAFC)[4,5]. The second category of new combustion technology is in the burner design, which includes Low NO_X Injection[6], Fuel Direct Injection[7] and Fuel/Oxidant Direct Injection[8]. It has been found that these new technologies have an advantage of lower pollutant emissions and higher combustion efficiency than traditional combustion.

The main characteristics of the flameless combustion are the uniformity of the heat flux distribution, the invisibility of the flame, the reduced aero-acoustic oscillations and the extremely low NO_X emissions. The flameless combustion is a phenomenon that has enormous emission reduction and improves combustion performance.

Suda *et al.,* 2002 investigated the flameless combustion characteristics and emissions under high temperature air combustion in a furnace of cylindrical shape power by pulverized bituminous and anthracite coal as a fuel. They found that there was a decrease in ignition delay and there was an enhanced rate of volatiles release. Also they found that the NO_X emissions was reduced by 40% when the preheated air temperature was increased during the experiment[9]. H. Zhang, *et al.,* 2007 and B. B. Dally, *et al.,* 2010 introduced a new design of burner, named Primary Air Enrichment and Preheating (PRP) burner. The PRP burner has a preheating chamber having one end connected to the primary air and the other end opened to the furnace. They found that when anthracite coal was used as fuel, a stable flame was obtained, and a 50% in NO_X emissions reduction was achieved when compared to low NO_X burners[10,11]. D. Ramona *et al.,* C. R. John *et al.,* and S. Hosseini *et al.* studied the formation of NO_X emission during flameless combustion using wood pellets as fuel. The results show that the level of NOx emission was proportional to the concentration of oxygen in the combustion air and to combustion air temperature. At high combustion air temperatures (1000ºC), the NO_X level increases rapidly with oxygen concentration in combustion air[12,13,14]. The effect of high preheat air combustion on NO_X emission was studied by Choi and Katsuki. They concluded that the Low NO_X emissions could be achieved even under high temperature[15]. This is one advantage of the flameless combustion over the traditional combustion technologies, which suffer from thermal NO_X when the combustion temperature increases[16,17].

The level of emissions of CO_2 and CO affected by the temperature and oxygen concentration in air combustion. When the temperature increases from 800 to 1000ºC at 5% oxygen dilution CO emissions increases from 10.1% to 11.0%. While the CO_2 formation was noticed at lower temperature and higher oxygen concentrations[12,14].

During the experimental work, it was observe that the flame is invisible, and was use as a self-recuperative burner. The furnace temperature is 1000°C and the preheated combustion air is about 650°C. At this condition the fuel is completely consumed without a visible flame[3], as shown in Figure 1. The results showed that the process, during the combustion was stable, NO_X emissions close to zero, low noise and smooth with low carbon monoxide content in the exhaust (< 1 ppm)[3].



A B

Figure 1 Direct photograph inside the present combustion chamber which represent (A) conventional flame mode and (B) flameless combustion system.

To achieve the flameless combustion, there are two fundamental requirements[3,19]. First, the process combustion temperature inside the chamber must be above the auto ignition temperature of the mixture (e.g., ≈800°C for natural gas -air). Second, the flue gas recirculation ratio which is the ratio between the fuel, oxidizer and diluted gas (flue gas, N_2 or CO_2) must be higher than three[20-22].

In this paper, the flameless combustion of natural gas with highly preheated air and CO_2 dilution was studies experimentally in a laboratory scale furnace in the High Speed Reacting Flow Laboratory (HiREF) at the Universiti Teknologi Malaysia.

2.0 EXPERIMENTAL SETUP

A schematic of experimental setup for the present study is shows in Figure 2. The test rig is made up of a horizontal combustion chamber of circular cross section. The combustion chamber is made of mild steel with length is 600 mm and the outer diameter of the chamber is 254 mm. The inner combustion chamber body was isolated with a 42 mm thick refractory material layer. The volume of this chamber is 0.054 m^3 .The combustion chamber is covered with 30 mm thick glass wool. In addition, the combustion chamber is equipped with a circular quartz window diameter of 50 mm fixed on the left side of the combustion chamber in order to perform flame imaging. The combustion air is preheated by a coil placed within the furnace assembly; its temperature adjusted up to 500°C. The preheated combustion air is injected through six 5 mm diameter holes and fuel is injected through a 5 mm diameter central hole. The flue gases are extracted at the other end of the combustion chamber through circular hole.

The test rig is prepared with several instrumentation systems to record the following variables. The air and fuel flow rates are measured using flow meters. Temperature of preheated air and the temperature of midplane along the combustion chamber are measured with K-type thermocouples. There are six holes for temperature measurements. The first hole, is placed at 60 mm from the burner, second, third, fourth, fifth and sixth at 135, 210, 325, 400 and 475 mm respectively from the burner. The accuracy of present thermocouple is about 2°C or 0.75% of reading whichever is greater. Temperature measured by the thermocouples is connected to a data acquisition system using the Picolog, model TC-08, software system and the results monitoring in the computer. Temperature measurement is sampled every one minute.

In the current project, the NO_X emission was measure inside the exhaust hole with Telegan Tempest 100 gas analyzer is used. The accuracy of present gas analyzer is about 5% for amount of emission more than 100 ppm.

The fuel used in the present work is natural gas where the composition is methane 92.73%, ethane 4.07% and other hydrocarbons 3.20%[23]. A cylinder of CO_2 was use for diluting of the combustible mixture. To measure the rate of NO_X emission for different combustion modes, several experiments are conducted. The effect of preheat and without preheat combustion air will be investigated in the present work. The equivalence ratio will took = 1.0 during all experiments; it is calculated based on stoichiometric equation and mass flow rate of fuel and air of each combustion condition. Thermal input power 7 kW where is calculated based on heating value multiply by fuel flow rate and all experiments are subjected by this value.

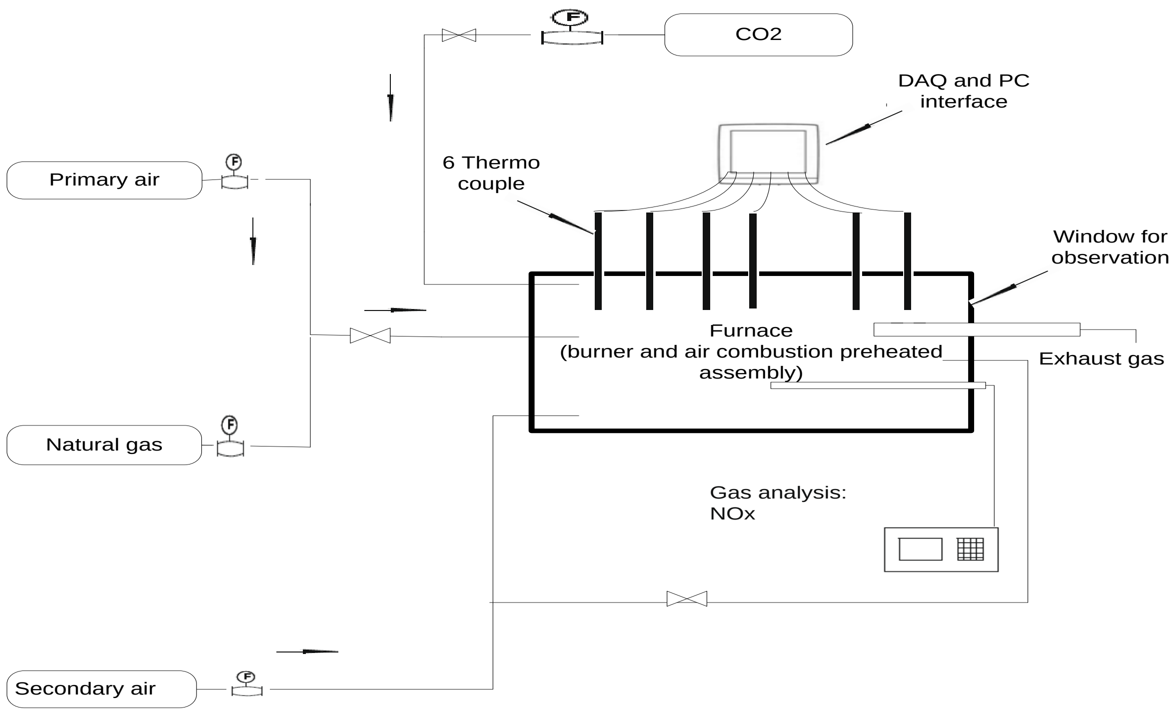


Figure 2 Schematic of experimental setup for flameless combustion system

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Determination of Threshold Temperature for Flameless Combustion

To establish flameless combustion, the furnace is heated using conventional flame until the threshold temperature is reaching. Then the fuel was shutting off until the flame is extinguished and then fuel is turned on again. In this process, the furnace temperature is maintained at above the threshold temperature. This is due to the flameless combustion regime critically depends on ambient temperature, which needs to be high enough to sustain chemical reactions even in the absence of flame front. In this study, a stable flameless combustion of natural gas was achieved at the average furnace midplane temperature above 800°C. This temperature was above the auto ignition temperature for natural gas. Figure 3 shows the exhaust gas recirculation k_v with furnace temperature was reported by A. Cavigiolo's in a laboratory-scale burner, using methane and ethane as fuel. From this study, it has been found that flameless combustion is established at chamber average temperatures of about 800-850°C, while using ethane as fuel, this value strongly decreases down to 600-650°C[24]. It is clear that in order to obtain stable flameless mode of natural gas in this study this threshold temperature needs to be reached or exceeded before the conventional flame could be shut off and switched to flameless combustion mode.

Figure 4 shows the combustion chamber temperature as function of time. The data in Figure 4 represent an average of three experiments at the same conditions. The difference in results between the three experiments was negligible, which proves the reproducibility of the experiments. The dashed vertical line represents the instant when the flameless combustion mode was activating. It happened by switching off the fuel for approximately one minute. The successful transition between conventional flame and flameless combustion modes is evidently associated with the sudden decrease in chamber reference temperature and drop of NO_X emissions. The low temperature gradient throughout the chamber is an important characteristic of flameless combustion mode. The characteristics of transition from conventional flame to flameless combustion in the present work agree well with the studies conducted by other researchers[25].

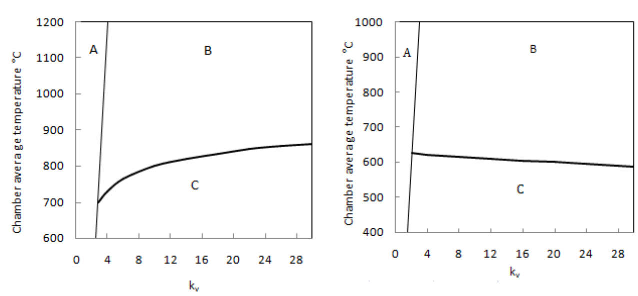


Figure 3 Combustion regimes map for methane (left) and ethane (right) in real-size burners:(A) conventional combustion zone; (B) flameless combustion zone; (C) no combustion zone[24]

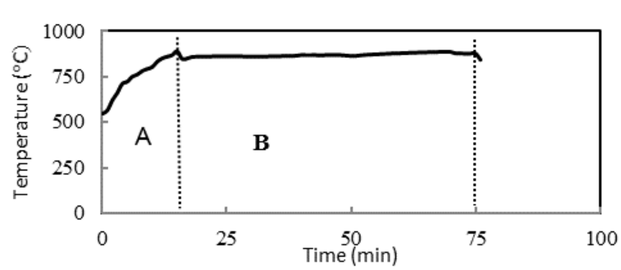


Figure 4 Variation of average temperature as a function of time from conventional combustion (A) to flameless combustion (B) for =1

3.3 Emissions of NO_X between Conventional and flameless Combustion

The average concentration of NO_X emissions are shown in Figure 5 for preheated air combustion, under operation condition (P= 7 kW, =1.0 and T_a = 500°C). The average values were taking from several measurement series, while the two series plotted in Figure 5 represent the series with highest divergence compared to the mean local values. After the activation of flameless combustion mode, there is a sharp decrease in NO_X concentration. This figure shows the NO_X emission decreased on the flameless mode compared with conventional combustion. The low NO_X emissions are in agreement with those reported for flameless combustion within the stable range. In order to show the effect of flameless combustion mode on the NO_X emission concentration, Figure 6 shows NO_X measurements plotted as a function of time during the activation of the flameless mode. The detailed explanation of the NO_X formation mechanism and its radical dependence on the presence of high-temperature reaction zone can be found in[3].

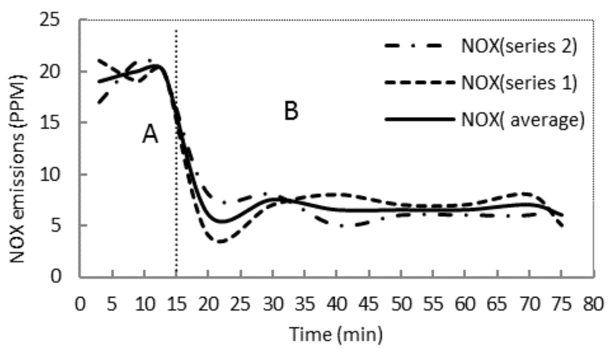


Figure 5 Average NO_X concentrations, plotted against time with preheated air for (A) conventional flame, (B) flameless

In Figure 7 the concentration of NO_X emissions was plotted with time without combustion air preheat under the operation conditions (P= 7 KW, =1.0 and T_a = 27°C). Flameless combustion was achieved without air preheat due to the temperature in the reaction zone is higher than auto ignition temperature of the reaction. This is in agreement with recent studies[26,27] which show flameless combustion can be achieved without combustion air preheat. Natural gas was dilute using CO_2 in both with and without combustion air preheating case. The natural gas and air mass flow rates were keeping constant during these experiments in each test. Figure 7 showed that the NO_X emission was reduced to lower than 7 ppm, compared when used air preheat.

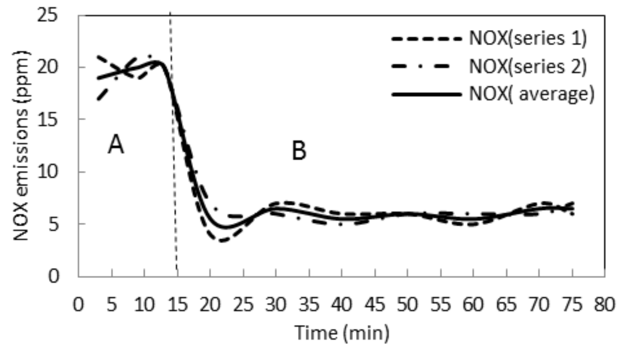


Figure 6 NO_X emissions as function of time at flameless mode with combustion air preheat

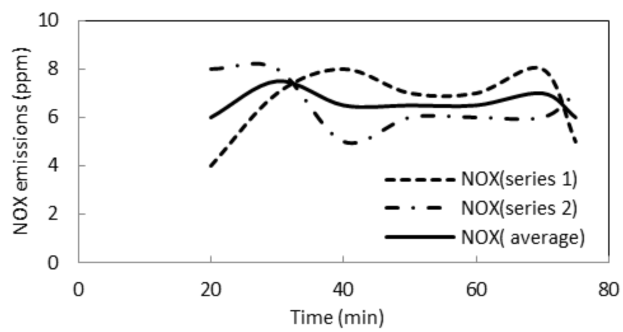


Figure 7 Average NO_X concentrations, plotted against time without combustion air preheat for (A) conventional flame mode, (B) flameless mode

Table 1 shows the comparison NO_X emissions (ppm) between several experimental works for different parameter. These data were taking from experimental works. It is shows that from table 1 the low NO_X emission that is recording in the present work is in a good agreement with reported for flameless combustion.

Table 1 Comparison of NO_X emissions (ppm) of natural gas for several experiment works

Reference	Equivalence ratio(Φ)	Fuel	NO_X(ppm)	Tair (°C)
Colorado *et al.*[28]	0.83	Natural gas (NG)	3	573
Effuggi *et al.*[21]	1.0	Natural gas (NG)	Less than 10	1300
Present	1.0	Natural gas (NG)	8	500
Present	1.0	Natural gas (NG)	7	27

■4.0 CONCLUSION

In this work, experimental study of flameless combustion have been done and the characteristic of this technology has been obtained. It was found that for stoicmetric mixture of natural gas-air, flameless combustion could be achieve from natural gas with and without preheat air. The transition from conventional mode to flameless combustion can be clear seen by significant reduction of NO_X emission throughout the combustion process. In these two cases, the NO_X emissions were of about 70% lower than the conventional combustion.

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